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Well Integrity: Modeling of Thermo-Mechanical Behavior and Gas Migration along Wells - Application to Ketzin Injection Well

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Abstract

Well integrity plays a key role in the overall performance of oil and gas projects, including Carbon Capture and Storage (CCS) projects. Well integrity has to be demonstrated over the well life-cycle, during operations (production, injection and/or monitoring), abandonment and few hundreds of years after closure, particularly to ensure effective CO_2 confinement into the reservoir.
To contribute to the development of CCS technologies at a commercial scale, a CO_2 injection experiment was developed in Ketzin, Germany. The project included drilling three wells: one for CO_2 injection, and two for CO_2 monitoring. The COSMOS 2 R&D project included wellbore integrity evaluation through extensive modeling at a meso-scale (well components scale) and a macro scale (well scale). The modeling activities focused on the fluids migration from the reservoir along the wellbore taking into account ageing mechanisms (e.g. casing corrosion and cement leaching) and micro-annulus opening at cement / casing / rock interfaces due to thermo-mechanical stresses.
Such modeling results have to be integrated in a pro-active risk-based management of well integrity in order to optimize design, define monitoring and maintenance action plan or demonstrate safety to authorities. The benefits are a good knowledge of the risks (causes and impacts), the assurance these are under control and, as a consequence, insurance of a secured investment.

Keywords: well integrity; CO_2 migration; micro-annulus; thermo-mechanical stress; ageing processes; modeling

1. Introduction, Context of the COSMOS2 and Well Integrity

To meet the climate challenge, Carbon Capture and Storage (CCS) is one of the most suitable technologies to reduce greenhouse gas emissions. Pilots projects are underway worldwide in an effort to

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progress to the industrial scale. Like in other Oil&Gas activities, wellbores constitute a major issue as it is the only intrusive man-made element that, by definition, links the target reservoir formation(s) to the surface. Wellbore integrity assessment bears a number of challenges, due to (i) time scales (short and long term), (ii) reactions/interactions between well components, geology and injected fluid and (iii) uncertainties associated with subsurface activities. Demonstrating that a wellbore is a safe barrier for CO_2 confinement over long term is of paramount importance for acceptance of large CCS technologies and industrial deployment.

The first European onshore carbon sequestration pilot project is taking place near the town of Ketzin, Germany. Three wells were drilled in 2007 for the project: one injection well and two monitoring wells. About 36,000 tonnes of CO_2 have been injected into a saline aquifer over two years; more information on project status and results is available in [1] and [2]. Among the research activities associated with the Ketzin injection site, the French-German COSMOS 2 research project included assessment of risks associated with wellbore integrity. This article presents the main results of the well integrity modeling performed on injection well Ktzi-201.

2. Risk-based Management of Well Integrity

In the COSMOS 2 project, the Ktzi-201 well was studied using a risk-based approach, the objectives were to:

- Assess if, over the long-term, the well could act as a conduit for CO_2 migration from the reservoir to other geological formations and/or to the surface;
- Quantify the distribution and evolution of these risks according to well parameters;
- Identify major contributors to CO_2 migration along the wellbore;
- Suggest relevant treatment actions to manage well integrity.

The main steps of the methodology used for the study are: (i) data collection and analysis, (ii) construction of a static model (geometry and properties of well components and geological formation) and a dynamic model (ageing processes, limit and boundary conditions of the well system); (iii) scenarios definition and simulation; (iv) risk quantification; and (v) recommendations regarding well integrity, see Fig. 1.

This article focuses on the three first steps of the methodology which include the modeling of CO_2 migration from the reservoir along the wellbore in consideration with the impact of thermo-mechanical stress, that could lead to micro-annulus opening at cement / casing / geology interfaces, and ageing processes (e.g. casing corrosion and cement leaching). Details on risk assessment methodology, risk values estimation and mapping are available in [3].

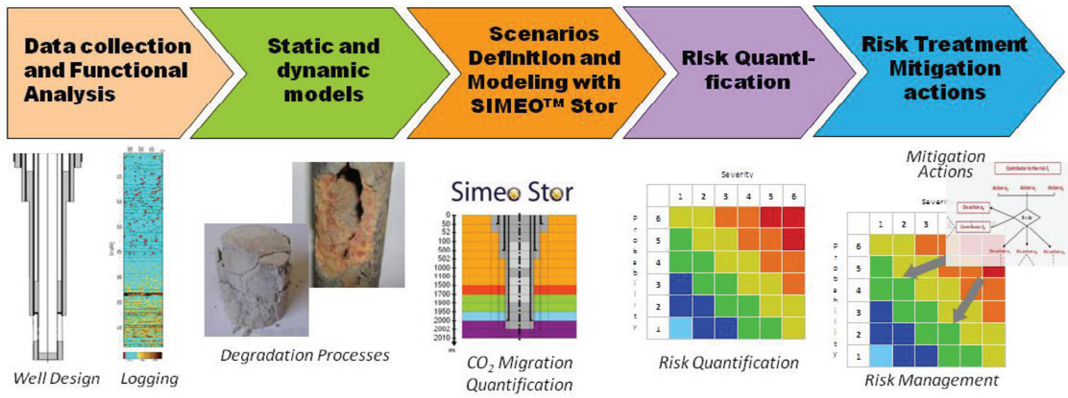

Fig. 1: Well Integrity Quantitative Risk Assessment Workflow

3. Well Ktzi-201 and Surrounding Geology

3.1. Well Geometry

Ktzi-201 was drilled to a total depth of 755 m in March of 2007. The main characteristics of Ktzi-201 design are described in [4]; only some specific information is reminded here. Note that, in a long-term perspective, only components which play a significant role in the long term containment of fluids are considered in the model: cement in the annuli and casings. Ktzi-201 has five different openhole sections and 5 different casing sizes. In Ktzi-201 well, there is no cement at the bottom of the annulus outside the 5½’’ production casing. Moreover, according to cement log data, no effective isolation can be expected from the last few meter of cement at the bottom of the 9⅝” cement annulus. As a consequence, these cement annuli will be immediately filled with CO_2 at the beginning of the injection.

As the objective of the study is the long-term performance of well Ktzi-201 (i.e. 1,000-year period), the well will be considered plugged and abandoned for the purpose of the study, even though it has not been abandoned yet. The abandonment strategy was defined according to best practice: two cement plugs were considered in the 5½” production casing, one at the top (close to surface) and one at the bottom (in front of perforations) of the well. The length of the cement plugs is respectively 50 m and 100 m. Cement plug quality is assumed to be good (low permeability value).

3.2. Geological Formations in Contact with the Injection Well

Geological formations define thermal, mechanical and hydraulic conditions to the well system. A simplified representation of the geology was considered (more information regarding geology can be found in [4]): the CO_2 reservoir (Stuttgart formation) at the bottom of the well (630 m – 710 m), a caprock (385 m – 630 m), and finally an overburden from top caprock to the surface, see Fig. 6 in the results section. The Initial reservoir temperature is about 33-35°C ([1] and [5]); the initial pressure is about 60-

61 bar ([1] and [2]). In the reservoir, the CO_2 is injected in a supercritical state, but it changes into a gaseous phase at a certain distance in the reservoir [1].

4. Well Integrity Modeling

4.1. Thermo-Mechanical Stress Inducing Micro-Annulus Opening

4.1.1. Objective

The objective was to assess the impact of the temperature and pressure conditions on the thermo-mechanical response of the well during CO_2 injection: potential cement failure and micro annuli opening at cement/casing/geology interfaces. These results were then used to determine the transport properties of the cement annuli (i.e. cement quality) at the end of the injection period. Transport properties are required in the fluid flow model to quantitatively estimate the CO_2 migration along Ktzi-201 wellbore over the long-term.

4.1.2. Models Description

The impact of thermo-mechanical stress during the injection phase was investigated by aFinite Element Method (FEM) analysis. In the simulations, the casing was modeled by thermo-elastic behavior with the assumption that applied stress is small enough to remain within elastic stress. The Cement and geology behaviors are described with non-linear models. The Ottosen model [6] was used for the cement to investigate crack width and the effect of plastic behavior after cracking. A simple elasto-plastic model was selected for the geology with a perfect plasticity and Mohr-Coulomb yield criterion based on the cohesion and friction angle (as simulation results show low stress, the perfect plasticity assumptions do not have any impact on cement failure and micro-annuli opening). The interfaces between casing / cement and cement / geology were modeled using joint elements with Mohr-Coulomb failure criterion. It allows to assess the occurrence of the opening at each interface and the order of magnitude of its width, see Fig. 2a. As a first conservative assumption, zero-bond strength was considered at the interfaces, meaning that any tensile stresses at cement / casing interface will lead to micro-annulus openings. Two case studies are described in this article:

- A first simulation assumes a perfect centering of casings;
- The second simulation is considered to assess the effect of casing eccentricity.

4.1.3. Ktzi-201 Well Section and Surrounding Geology

A section of Ktzi-201 below the injection packer was considered to assess the impact of CO_2 injection on the thermo-mechanical response of the well. The depth of 565 m was selected as the CO_2 will be in direct contact with the inner surface of the 5½" casing. At this depth, the 5½" casing is cemented in the 9⅝" casing, itself cemented in a 12¼" borehole, see Fig. 2a. The Casing thicknesses are 0.361 and 0.35 inch respectively. The cement is a standard class-G mixed with fresh water and no chemical additives. The casings are grade K-55 steel. 5½" casing has a 13Cr80 outside coating [4], but it was not considered for the simulations. Typical mechanical and thermal properties are used for the cement [7] and the casings (Table 1). The cement compressive and tensile strength limits are 48 and 4.8 MPa respectively; the fracture energy is 40 N/m.

At 565 m depth, Ktzi-201 is surrounded by an anhydrite rich formation that has a high thermal conductivity (≈ 4.5 W/m.K) in comparison with the other geological formations below and above [8]. The initial temperature at 565 m depth was set to 32°C and the initial fluid pressure at 6 MPa. Similar assumptions to [9] for the mechanical properties of the geology, were considered (see Table 1). In the simulations, the rock cohesion coefficient was set to 20 MPa, and the friction angle to 27°. In the model, the geological formation surrounding the outer cement was considered long enough to remain at the initial temperature during the simulation. The outer boundary was fixed (no strain condition): the rock was considered sufficiently rigid to avoid any movements due to the injection pressure, see Fig. 2b. No mechanical stress from the geology was applied to the outer cement annulus.

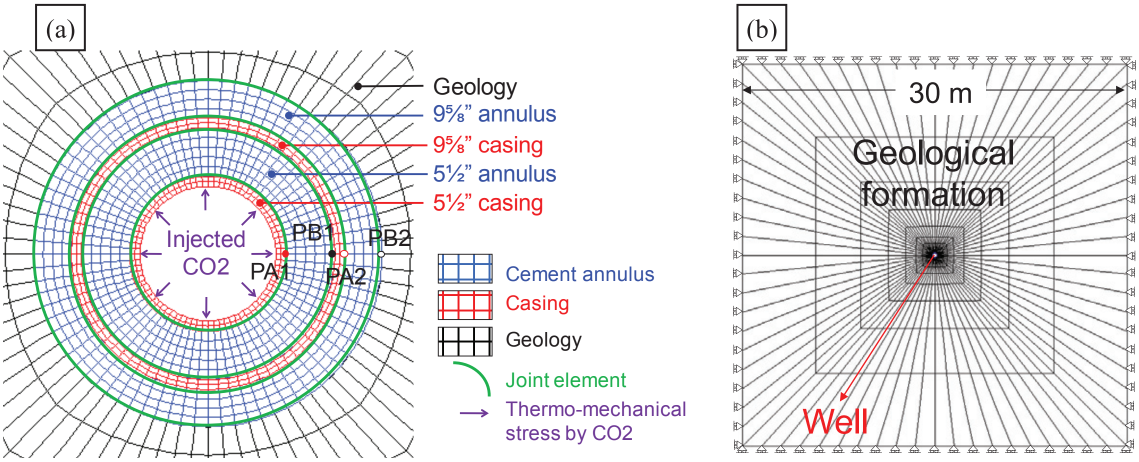

Fig. 2: (a) 2D Section of Ktzi-201 Well Model at 565 m Depth (Assuming Perfect Centering of Casings); (b) Complete View of Model Mesh with Boundary Conditions

Table 1: Material Properties

Material	Thermal Conductivity [W/m·K]	Specific Heat [J/m^3·K]	Density [kg/m^3]	Young's Modulus [GPa]	Poisson's Ratio [-]	Thermal Expanding Coeff. [μ/°C]
Casing	54	3.69 x 10^6	7850	200	0.3	14
Formation	4.5	3.0 x 10^6	3000	20.0	0.29	10
Cement	1.0	4.0 x 10^6	1900	8.5	0.13	10

4.1.4. CO_2 Injection Conditions

The CO_2 injection conditions were applied to the inner surface of the 5½" casing, see Fig. 3a. These conditions were defined based on the data presented from the previous articles describing CO_2 injection at Ketzin [5] and [10]. Due to computation time constraints, and since it was demonstrated to have no impact on the results, a CO_2 injection period of 6 months was considered instead of 2 years, including a shut-in sequence, see Fig. 3a. The maximal CO_2 temperature is set to 37°C; the maximal injection pressure to 7.5 MPa.

4.1.5. Results

The temperature and stress values (tangential and radial) were investigated at different point of interest: at inner surface of cement annuli (PA1 and PA2), and at outer surface of cement annuli (PB1 and PB2), see Fig. 2a. The results show a rapid temperature transfer from the injected CO_2 to the 5½" casing cement annuli and geological formation, see Fig. 3b. The temperature at PB2 increases up to 34.5°C. The initial thermal swelling of casings causes a rapid increase in tangential and radial stresses at inner surfaces of both inner and outer cements annuli, see Fig. 3c and d. The maximum stresses in the cement are observed at the outer surface of 5½” casing (PA1), see Fig. 3c, where the greater temperature evolution is observed. However, stresses remain very small and do not lead to radial cracks and failures. In this case, no micro annulus at cement / casing or cement / formation interfaces is observed during CO_2 injection and shut-in. Results show that there is a low probability for a micro-annulus to open for these test conditions.

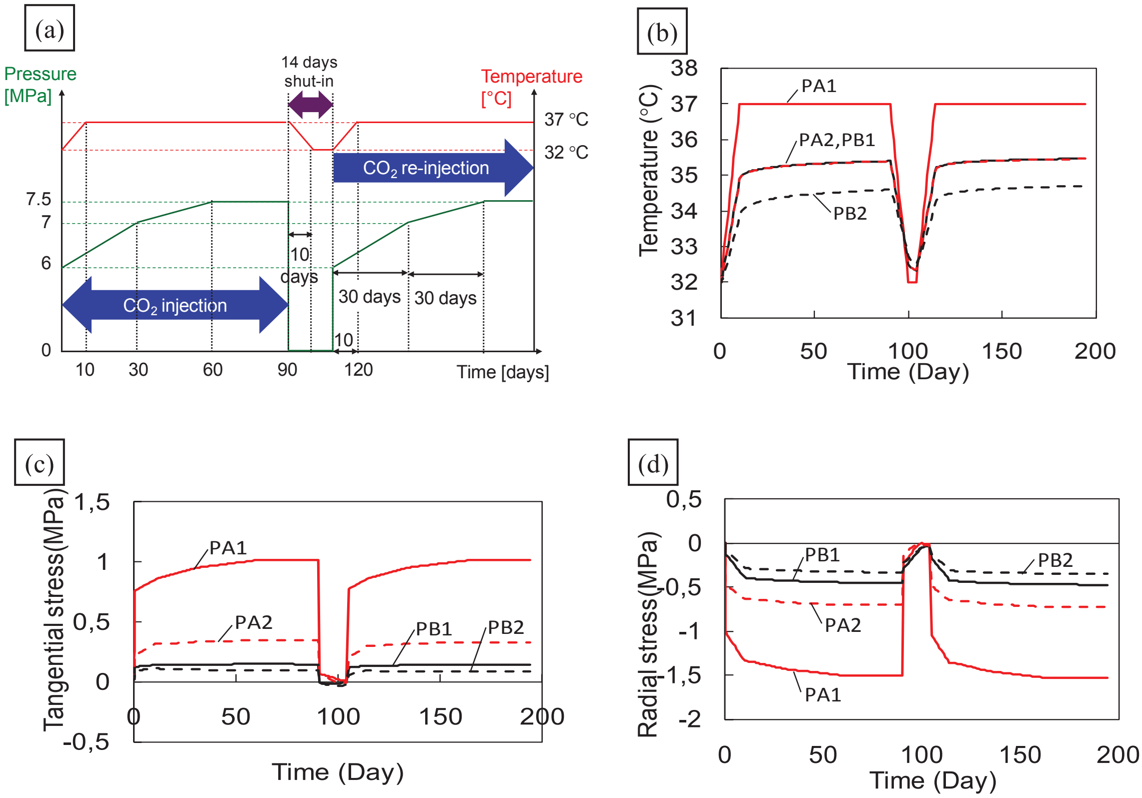

Fig. 3: (a) CO2 Injection Temperature and Pressure; and Ktzi-201 Response in Terms of (b) Temperature, (c) Tangential Stresses and (d) Radial stress for Perfect Casings Centering

A similar simulation was performed considering an eccentricity of 40% for the 5½” casing (an eccentricity of 100% being the worst eccentricity possible). The same CO2 temperature and pressure profiles were applied to the 5½” casing; the main results are summarized in Fig. 5a. In this case, although there are no crack and micro-annulus either, the tangential tensile stress in the cement increases with the casing eccentricity. The greater tensile stress is still at the inner surface of the 5½” annuli, but its value approaches the cement tensile strength limit, see Fig. 5c and d. Some additional simulations not presented here showed that an eccentricity of 85% would exceed cement tensile strength limit at the thinner side of 5½” cement annulus. Fortunately, centralizers were set outside Ktzi-201 5½” casing to ensure good positioning of the production casing and minimize eccentricity [11]. However, these steel pieces placed outside the casing could induce local micro-annulus opening (not studied in this article).

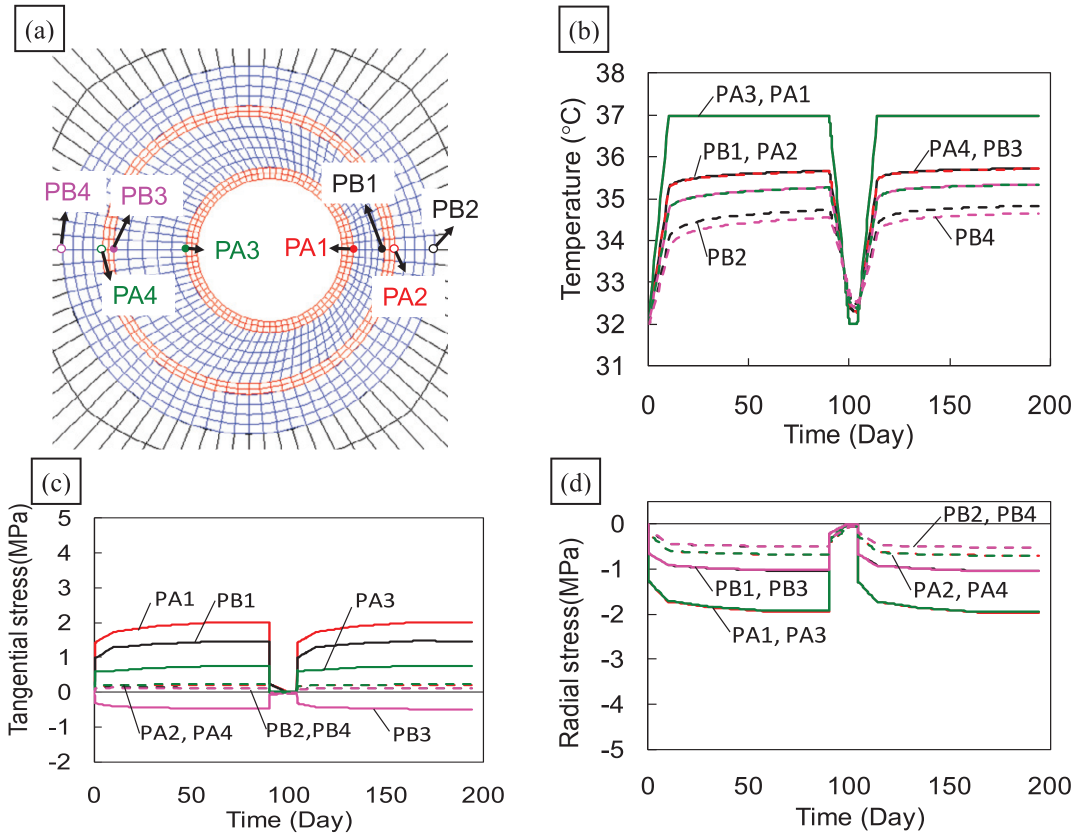

Fig. 4: (a) Geometry for a 40% Eccentricity; and Ktzi-201 Response in Terms of (b) Temperature, (c) Tangential Stresses and (d) Radial stress for a 40% Eccentricity Geometry

4.2. Gas Migration Modeling along Ktzi-201

4.2.1. Objective

The objective of the fluid migration model is to estimate, in the long term, CO_2 upwards migrations from the reservoir along Ktzi-201 wellbore. One key characteristic of the model is the coupling of fluid flow with ageing mechanisms of the well's components. In the long-term (i.e. after end of injection) ageing mechanisms have the greater impact on well components deterioration.

4.2.2. Transport Properties of Annuli

In the long-term, transport properties of annuli depends on (i) the cement permeability after drilling (including the potential presence of defects, channels, debonding, etc.), (ii) the impact of thermo-mechanical stress during operations (i.e. CO_2 injection in this case) and (iii) ageing processes such as cement leaching by formation fluids and carbonation in the presence of CO2. In the flow model, the initial transport properties are defined as a combination of (i) and (ii), while the impact of ageing processes is directly considered in the model. As shown previously, thermal and mechanical stresses due to CO_2 injection are not an issue in Ktzi-201, therefore, initial annuli transport properties are driven by the permeability after drilling. According to logs, and experts' feedback, permeability in the annuli after drilling was defined as rather poor due to some debonding, resulting in permeability values above the milliDarcy.

4.2.3. Chemical Degradation Processes Impacting Cement and Casing Components Over Time

Cement leaching and casing corrosion are the two major long-term ageing processes that will affect well components and increase their transport properties over time. Leaching of cement hydrates in the presence of formation fluids (see Fig. 5b) is due to a difference in chemical equilibrium between the cement pore solution (pH ≈12-13) and the formation fluids (pH ≈ 6-7). Leaching results in an increase of cement porosity and permeability over time (see Fig. 5b, [12]). Casing corrosion is assumed to initiate after pH drop once cement is completely leached (see Fig. 5c), and end by casing breakthrough (see Fig. 5e.). More details on degradation processes considered in the model are available in [3].

The presence of a CO2–rich environment in contact with cement-based materials also induces chemical degradation, i.e. carbonation. The latest articles show that the carbonation process for wellbore cements could have a positive impact on cement transport properties (i.e. permeability drop) due to precipitation of carbonates as discussed by [13] and [14] for example.

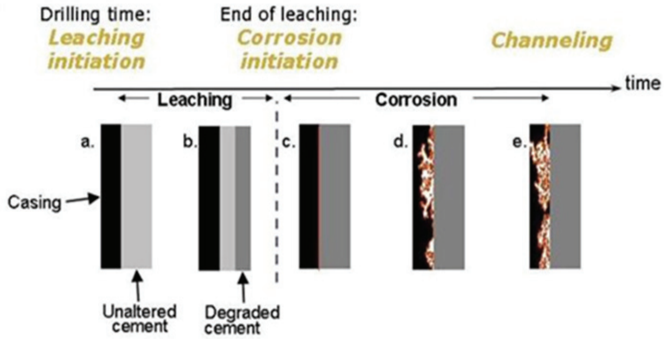

Fig. 5: Cement leaching and Casings Corrosion in the Cement Annuli

4.2.4. Reservoir Pressure Profile

A simplified pressure profile was considered: the pressure at the bottom of the well system (top of the Stuttgart formation) was considered to be equal to 7.3 MPa over the two years of injection; decreasing linearly down to the hydrostatic pressure over the following 48 years; and finally to remain constant at the hydrostatic pressure during the following 950 years.

4.2.5. CO_2 Migration Results

Based on the various parameters considered in this study, several scenarios have been defined. A scenario is defined as a particular state of the well, i.e. a set of specific values assigned to each parameter (within the range values defined). The SIMEO^{TM} Stor platform has been used to run the scenarios and assess CO_2 migration along the wellbore over time. Details about the software can be found in [15].

An illustration of a simulation results is given in Fig. 6. In Fig. 6, the blue zones in the well system are water saturated zones (not affected by CO_2) and the red zones contain some CO_2 coming from the reservoir. Fig. 6a shows the initial state of the Ktzi-201 well, as explained previously, CO_2 is present since the beginning as there is no cement in the 5½" annulus. For this scenario, Fig. 6b shows that after 1,000 years, CO_2 remains confined within the wellbore, below top of the caprock. CO_2 migrates in the bottom part of the 9⅝" and 5½" cement annuli. Some CO_2 has penetrated inside the 5½" production casing because of the corrosion of the 5½" casing from the outer surface. Corrosion occurs in zones exposed to CO_2 over the 1,000 years of simulations.

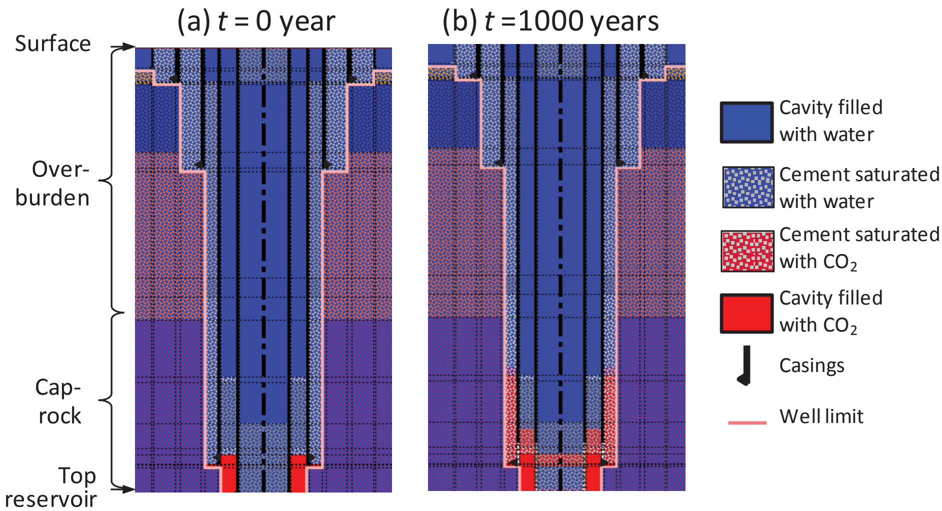

Fig. 6: Gas Migration Modeling Results (a) Initial CO_2 Saturation; (b) CO_2 Saturation after 1000 Years

5. Conclusion

The Ktzi-201 well integrity was studied in details through modeling of micro-annulus opening and cement cracking during the injection phase, and CO2 migration along wellbore in the long-term after well plugging and abandonment.

Thermo-mechanical simulations' results show that there is a low probability that micro-annulus will open at cement/casing interfaces during CO_2 injection. In Ktzi-201, the inner surface of the 5½" cement annulus withstands the greater tangential stress, but only an, unlikely, high casing eccentricity could increase stresses up to the cement tensile strength limit. The absence of micro-annulus contributes to maintain good cement isolation properties during the injection phase. In the long-term, chemical degradation processes becomes predominant and deteriorates the confinement properties of both cement annuli and casings. However, simulations results show that CO_2 remains confined below the top of caprock over the following 1,000 years.

The approach and the simulations results presented in this article are part of a global risk-based approach that provides an objective support for decision making regarding management of well integrity in the short and long-term. Results have to be used to optimize operations (pressure and temperature of CO_2 during injection), define abandonment strategy (design and location of cement plugs, [3]) and support the safety demonstration with respects to CO_2 confinement in the long-term (identification of leakage paths, quantification of CO_2 that migrate from the reservoir into the wellbore).

Acknowledgments

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